Biochar and Cementitious Composites

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Cementitious materials are one of the most used infrastructure materials worldwide due to their low cost, well-developed production methods, and well adaptability to varying environmental conditions. Cementitious composites are mainly divided into three groups, i.e., concrete, mortar and paste. Being quasi brittle, they are prone to cracking, which greatly compromises their strength and durability. Due significance has been given to mitigate the brittle behavior of cementitious composites in the past: Various studies are available, intended at improving the tensile strain capacity of the cementitious materials. Apart from conventional steel reinforcement, inclusion of fibers has remained the focus of many studies.

cementitious composites fracture energy pyrolysis biochar high performance

1. Overview

In cement composites, usually, reinforcement is provided to restrict the crack development and their further propagation under service conditions. Typically, reinforcements utilized in cementitious composites range from nanometer scale to millimeter scale by using nano-, micro-, and millimeter-sized fibers and particles. These reinforcements provide the crack arresting mechanisms at the nano/microscale and restrict the growth of the cracks under service loads, but usually, the synthesis of nano/microfibers, and afterward their dispersion in the cementitious materials, pose difficulty, thus limiting their vast application in the construction industry. Carbonaceous inerts are green materials since they are capable of capturing and storing carbon, thus limiting the emission of CO_2 to the atmosphere. In the present study, a comprehensive review of the synthesis of low cost and environmentally friendly nano/micro carbonaceous inerts from pyrolysis of different agricultural/industrial wastes, and afterward, their application in the cementitious materials for producing high performance cementitious composites is presented, which have the potential to be used as nano/micro reinforcement in the cementitious matrix.

2. Background

Cementitious materials are one of the most used infrastructure materials worldwide due to their low cost, well-developed production methods, and well adaptability to varying environmental conditions. Cementitious composites are mainly divided into three groups, i.e., concrete, mortar and paste. Being quasi brittle, they are prone to cracking, which greatly compromises their strength and durability [1][2][3]. Due significance has been given to mitigate the brittle behavior of cementitious composites in the past: Various studies are available, intended at improving the tensile strain capacity of the cementitious materials. Apart from conventional steel reinforcement, inclusion of fibers has remained the focus of many studies [4][5][6].

Fiber-reinforced cementitious materials consist of synthetic or natural materials. The fibers are intended to provide resistance against cracking both in plastic and hardened forms of composite materials. The synthetic fibers comprise metals such as steel, aluminum or polymers such as polypropylene, polyester, nylon, acrylic, aramid, and carbon [7]. The natural fibers include coir, jute, pineapple leaf, kenaf bast, bamboo, palm, hemp, sugarcane bagasse, etc. [8][9]. In the following paragraphs, a brief introduction to the application of fibers in cementitious materials is presented.

Eren et al. studied the effect of steel fibers on the tensile strength of concrete [10]. Their study revealed that steel fibers with an aspect ratio of 80 and fiber content of 1.5% can increase the tensile strength of the concrete by 111%. Tiberti et al. evaluated the capability of steel fiber reinforced concrete in controlling cracks and reducing crack spacing [11]. They have reported that the crack spacing reduced by 30% with 0.5% fiber content and by 37% with 1% fiber content. Pająk et al. evaluated the flexural behavior of self-compacting concrete reinforced with straight and hooked-end steel fibers (0.5, 1.0, and 1.5% volume content) [12]. They have concluded that the fracture energy increased with the increase in fiber content and the fracture energy is always greater for hooked end fibers at the same dosage. Doo-Yeol et al. studied the tensile performance of ultra-high-performance concrete through straight and half-hooked steel fibers [13]. They have reported that a lesser quantity of hooked fibers, compared to the straight ones, is required for the same tensile strength. Düzgün et al. studied the effect of steel fibers on strength of lightweight pumice aggregate concrete [14]. They have reported that the reinforcement increases both strength and ductility up to 1.5% fibers. Vandewalle studied the cracking behavior of concrete beams, reinforced with combined longitudinal steel rebars and steel fibers [15]. They have reported that the combined reinforcement reduces both the crack spacing and the crack width.

Alhozaimy et al. examined the mechanical properties of concrete reinforced with polypropylene fibers (below 0.3% fiber content) [16]. They have reported an increase of 387% in flexural toughness at 0.3% fiber content. Kakooei et al. studied concrete samples reinforced with 0–2 kg/m^3 polypropylene fibers. They have reported that reinforcement of 1.5 kg/m^3 gives optimum results vis à vis compressive strength of the concrete [1]. Afroughsabet et al. evaluated the strength and durability of high strength concrete, reinforced with steel and polypropylene fibers [17]. Their resulting concrete at failure is shown in Figure 1. They have reported that 1% steel fibers enhance the splitting tensile and flexural strengths significantly. They have also claimed the best performance with 1% hybrid combination (0.85% steel and 0.15% polypropylene), with regard to mechanical strength, electrical resistivity and water absorption. Song et al. investigated the mechanical properties of concrete reinforced with nylon and polypropylene fibers at a dosage of 0.6 kg/m^3 [18]. They have reported that nylon-reinforced concrete had superior strength, and crack-resistant properties than the polypropylene reinforced one. They have attributed the enhanced properties to higher tensile strength and better distribution of nylon fibers in concrete matrix than the polypropylene fibers.

Figure 1. Concrete reinforced with steel and polypropylene fibers, reprinted with permission from Afroughsabet, Vahid., Ozbakkaloglu, and Togay. Elsevier.

As far as the incorporation of natural fibers is concerned, there are some problems, as pointed out by various researchers, which need to be addressed prior to their application for reinforcement in cementitious composites: The natural fibers have a degrading effect in alkaline cementitious environments, and their pretreatment is required prior to the utilization [19]. Bilba et al. studied the silane-treated bagasse fibers in cementitious materials, using two silane, alkyltrialkoxysilane and dialkyldialkoxysilane [20]. The SEM images of the composites reinforced with bagasse ash fibers with and without saline treatment are shown in Figure 2. Their study revealed that saline treatment improves the water resistance of the fibers and make them hydrophobic. Andiç-Çakir et al. studied the mechanical properties of coir fiber-reinforced cementitious mortars. Their study revealed that the alkali-treated coir fibers enhanced the compressive and flexural characteristics of the mortars [21]. Khan et al. studied the effect of 5 cm long coconut fibers on the strength of concrete with a fiber content of 2% by mass of cement [22]. They have reported 15% silica fume, 2% coconut fibers, and 1% super plasticizer as the optimum mix composition for enhancing the strength and cracking resistance of the mortars. Islam et al. evaluated the effect of jute fibers on concrete properties [23]. Their study revealed that smaller fiber content (0.25% by mass of cement) had positive effect on the strength of the concrete.

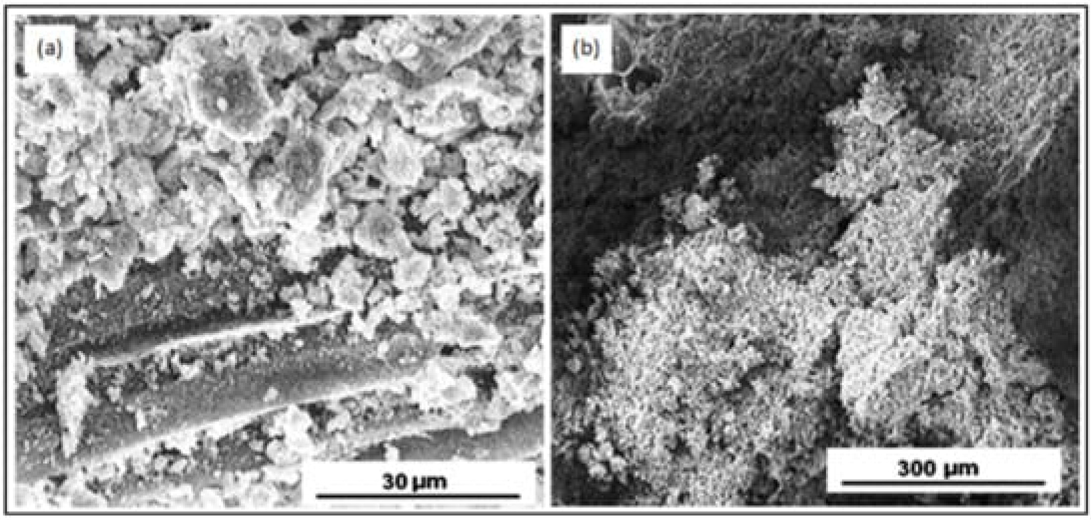

Figure 2. SEM images of composites: (**a**) composite reinforced with bagasse fiber and (**b**) composite reinforced with bagasse fiber treated with silane, reprinted with permission from K. Bilba and M. Arsene. Elsevier.

Many researchers have outlined the problems with natural fibers, including their biodegradation in an alkaline environment, their non-uniform distribution, and balling effect at higher fiber doses [19]. Special techniques, such as silane treatment, can address the issues encountered with the use of natural fibers as a crack-arresting medium in cementitious composites. Apart from fibers, another cost-effective method to enhance the fracture energy and crack resistance of the cementitious composites is the use of carbonaceous inerts (biochar) obtained from pyrolysis [24]. The biochars are reported to retain carbon from hundreds to thousands of years; thus, the synthesis and use of biochar are highly ecological, reducing the discharge of CO_2 back to the atmosphere [25]. This review paper intends to address the enhancement of crack resisting properties by using carbonaceous inerts obtained from pyrolysis of different industrial, municipal, and agricultural wastes.

3. Conclusions

Biochar is a versatile material having a high potential for utilization in various fields. In the current paper, a brief summary of the literature has been reported on the subject with emphasis on the pyrolysis mechanism, the influence of operating conditions on the final products, and its potential application in the production of high-performance cement and concrete composites.

It is concluded that biochar may be produced from almost all types of feedstock; however, the characteristics of the final product strictly depend upon the constituents of the feedstock and operating conditions. On the basis of numerous research studies, it is concluded that slow pyrolysis up to 300 °C produces the optimum yield since this temperature is sufficient to decompose the cellulose, hemicellulose, and lignin effectively. The operating pressure plays an important role by increasing the biochar yield with lesser energy requirements at higher pressures.

The useful application of biochar in cementitious composites has been highlighted by various researchers and is presented in Figure 15. In cement and concrete composites, biochar produces a positive effect by increasing the strength due to the internal curing mechanism and pore refinement effect. The introduction of biochar also tends to enhance the fracture energy and tensile load carrying capacity due to the phenomenon of crack entrapment, crack bridging, and crack contouring.

However, almost all researchers have reported that the workability/flowability reduces with the incorporation of biochar in the cementitious composites, which can be overcome by using flow-enhancing admixtures. Nevertheless, the reinforcement of cementitious composites with biochar is an effective method of carbon sequestration, which is beneficial to human health and the environment.

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